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MODELLING WAVE ENERGY RESOURCES IN THE IRISH WEST COAST

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ABSTRACT

In order to assess the potential wave energy extraction, a study is made to validate a model that can be used to characterize Ireland's wave climate in a more extensive study. The target area is the Irish West Coast, known for having the highest average wave power in Europe. The wave conditions in the coastal area were characterized by coupling the wave models SWAN and WAVEWATCH III. Validation tests are carried out with buoy data so that the model's performance can be evaluated. The wave parameters considered for the comparisons in the time domain are significant wave height and mean period, and the spatial distribution of wave energy is examined in a case study. Theoretical values of wave power are obtained for sites close to the coast and in particular for the two tests sites of Galway and Belmullet.

Keywords: *Renewable Energy, Wave Power, Irish Nearshore, Spectral Models*

1 INTRODUCTION

Traditional methods of energy production are contributing to serious environmental problems. Since the world energy consumption is estimated to rise over the next decades, the energy sector was forced through a renovating process, which sees an opening towards renewable energy. Wave energy is generally considered to provide a clean resource of renewable energy, with limited environmental impacts.

Wave energy comes from the winds, as they transfer it to the ocean's surface. Once created, waves can travel thousands of kilometers with little energy loss. The power in the wave is proportional to the square of the amplitude and to the period of motion. Therefore, long period (~7-10) and even relatively small amplitude (~2m) waves have energy fluxes commonly averaging between 40 and 70 kW per m width of oncoming waves. Nearer the coastline the average energy intensity of a wave decreases due to interaction with the sea bed. The highest energy ocean waves are concentrated off the western coasts in the 40-60º latitude range north and south.

Waves are bigger and more powerful along the western edge of the Earth's continents because of the prevailing west-to-east winds. The annual average power in the wave fronts varies in these areas between 30 and 70 kW/m (Figure 1), with peaks up to 100 kW/m in the Atlantic SW of Ireland, in the Southern Ocean and close to Cape Horn [1].

Although, wave power is seen as a large source of energy, the limited experience makes it possible to form only an incomplete picture of possible impacts caused by wave power devices. There are also difficulties facing wave power developments, such as irregularity in wave amplitude, phase and direction and the structural loading in the event of extreme weather conditions. On the other hand, the advantages of wave energy are obvious, as it combines crucial economic, environmental, ethical and social factors [2].

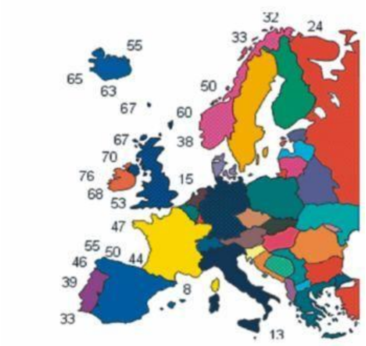

Figure 1 - European Wave Energy Atlas, Average Theoretical Wave Power (kW)

Various wave energy technologies are currently being developed based on different principles. The different systems may be classified according to their proximity to the coastline as shoreline, nearshore and offshore systems [3]. Their respective water depths ranges from 15m, 15 - 30m, 30 - 50m. Shoreline systems were the first to be developed. For structures in, or near, the surf zone, the downsides can disappear in the case that the converter can be integrated into a new coastal structure, but it is still of limited application. As regards nearshore or offshore energy converters, the distinction is not so clear-cut. Generally speaking, offshore installations appear best suited for providing energy to the general electricity network, while nearshore installations may be more appropriate where the aim is to supply a specific industry, such as a desalination plant [4].

In terms of potential usefulness, the wave climate off the West coast of Ireland is one of the most favorable in the world and certainly the most conveniently placed. The average annual wave height in deep waters off the Mayo / Donegal coast is over 3.5 meters, with a period of close to 10 seconds. In winter months the figures are much higher. In energy terms, wave power for January regularly exceeds 150 kW/m length [5]. Developing renewable energy is an integral part of Ireland's sustainable energy objectives and climate change strategy. There are currently a number of wave energy devices being tested in the Galway Bay test site for quarter devices and it has also been announced the development of a full scale test site off the west coast of Ireland, at Belmullet [6].

The potential for wave energy extraction can be obtained from analysis of the wave climate. Real data can give a general idea of the existing conditions offshore, but there are some limitations due to the fact that the time period of measurements may be limited. Therefore, the interest is to develop a system that is able to predict the wave characteristics in various locations for whatever period of time, and it can be done with numerical models.

Various studies have been carried out in this general area, one of which by Pontes *et al.* [7], where a nearshore wave atlas has been developed for Portugal. The atlas presented in this study uses a hindcast of directional wave spectra for an 11-year period, produced by the MAR3G model, which is similar to the WAM model, and directional spectra are transformed from open ocean to nearshore by using an inverse-ray model.

Presently much larger data sets of meteorological and wave data are available, allowing a better characterization of the wave climate. A 44-year wave hindcast for the North East Atlantic European coast has been performed by Pilar *et al.* [8], in the context of the HIPOCAS project [9]. The hindcast wave model used was WAM modified for two-way nesting. The output parameters were significant wave height, wave direction, mean and peak period, wind speed and direction, *Hs* for wind sea, direction of wind sea, *Tm* for wind sea, *Hs* for swell, direction for swell and *Tm* for swell.

This study was complemented by another one developed by Rusu et al [10], which couples WAM for deep water conditions and SWAN for nearshore results, which represents a higher quality prediction than the one using a ray model. A regional meteorological model was also used in the coastal area and it was found that the skill of the model was improved with the finer grid wind fields [11].

This system coupling WAM and SWAN was then used and validated by Rusu and Guedes Soares [12] to produce estimates of wave energy in coastal areas, showing how the wave energy decreases as one approaches the shore.

The same general approach is now applied to Ireland's west coast, with the aim to validate a model intended to evaluate its wave energy potential through the modeling of its wave conditions nearshore. Most data available for this area is offshore and, therefore, the aim is to obtain energy estimates nearshore, considering the effects of the bathymetry, using the SWAN model.

Comparing with the earlier studies referred above, in this work the WAVEWATCH III (WWIII) model is being implemented instead of WAM, but the goal is to do a similar study as the one done for the HIPOCAS project [9], having now the output of wave energy values instead of wave parameters. This is a first approach to an extensive work that is being developed in the framework of a European project with the aim of to provide resource information to the marine renewable energy sector.

2 DESCRIPTION OF THE WAVE HINDCAST SYSTEM

The wave hindcast system implemented uses the WWIII model for wave generation, covering almost the entire North Atlantic basin, whereas SWAN model is used for wave transformation in the coastal environment.

WAVEWATCH III ™ Tolman [13] is a full-spectral third generation wind-wave model. It has been developed at the Marine Modeling and Analysis Branch (MMAB) of the Environmental Modeling Center (EMC) of the National Centers for Environmental Prediction (NCEP) and is distributed freely.

Like other numerical model de Eulerian form of the balance equation

$$\frac{DS}{Dt} = \frac{S}{\sigma} \tag{1}$$

is needed.

This formula can be written in a transport equation form, or in the conservation form. The conservation form is valid for the vector wavenumber spectrum N(k,x,t) only, whereas valid equations of the latter form can be derived for arbitrary spectral formulations and the corresponding jacobian transformation is well behaved (e.g., Tolman and Booij) [14].

Balance equation for the spectrum N(k,ө;**x**,t) used in the WAVEWATCH III ™ is given as:

$$\frac{\partial N}{\partial t} + \nabla_x \cdot \dot{x} N + \frac{\partial}{\partial k} k N + \frac{\partial}{\partial \theta} \dot{\theta} = \frac{S}{\sigma} \tag{2}$$

$$\dot{x} = c_g + U \tag{3}$$

$$\dot{k} = -\frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial s} - k \cdot \frac{\partial U}{\partial s} \tag{4}$$

$$\dot{\theta} = -\frac{1}{k}\left[\frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial m} - k \cdot \frac{\partial U}{\partial m}\right] \tag{5}$$

Here σ is the relative frequency, k is the wavenumber vector, U is the (depth and time – average) current velocity, c_g is given by θ and c_g, s is a coordinate in the direction θ and m is a coordinate perpendicular to the coordinate s. The equation (2) is valid for a Cartesian grid. For large scale applications, this equation normally is transferred to a spherical grid, but maintains the definition of local variance. The spherical grid is defined by longitude λ and latitude φ.

The model general source terms used in WAVEWATCH are defined as :

$$S = S_{\ln} + S_{in} + S_{nl} + S_{ds} + \ldots \tag{6}$$

In deep water it can only considered for S the following terms. S_{nl} is a nonlinear interaction wind wave, S_{in} is the wind wave interaction and S_{ds} is a dissipation term. For model initialization it should also consider S_{ln} which is a linear input.

The wave model SWAN [15] (Simulating Waves Nearshore) is an extension of deep water third-generation models, this was developed at Delft University of Technology, it is fully spectral and computes the evolution of wind waves in coastal regions. SWAN and WWIII are both widely used spectral wave models that have been validated in a wide range of situations. Both models are governed by the same principle, where the evolution of the wave spectrum in space and time is described by conservation of action density being balanced by source terms representing generation, dissipation, and wave-wave interaction processes. The action density is the energy density divided by the relative frequency. WWIII tends to be more efficient at global scales, whereas SWAN offers advantages at smaller scales and its specific consideration of shallow water processes.

SWAN's domain boundaries must be located in WWIII grid where shallow water effects do not dominate, to avoid discontinuities between models. In SWAN, the source/sink term from equation (6) includes physical processes of generation, dissipation and non-linear wave-wave interactions in shallow waters such as wind input, whitecapping, bottom friction, depth-induced breaking and triad wave-wave interaction [16].

Recent developments in SWAN allow it to be used quite successfully for sub oceanic scales. For this reason, the wave prediction system adopted considers a large SWAN domain that covers the entire west coastal environment and connects the large scale to the coastal simulations.

The characteristic for the computational grids, for both WWIII and SWAN domains, are displayed in Table 1. Figures 2 and 3 illustrate the domains specified.

WW III was implemented with data acquired from two NOAA datasets. The bathymetry came from GEODAS database and the wind fields were taken from NCEP's Reanalysis 2, with time steps of 6 hours (4x daily data). The results are generated with a time step of 3 hours. Afterwards, WWIII data are used as boundary conditions for SWAN. For the SWAN runs, the wind fields considered are the same as in WWIII, but the bathymetry for Belmullet and Galway Bay's A1.2 regions were taken from GEBCO's database, while Galway Bays's A1.2.1 was provided by the Martin Ryan Marine Science Institute, at NUI Galway.

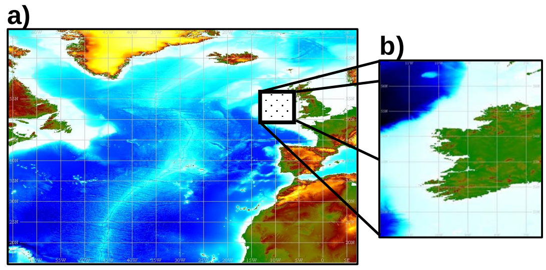

Figure 2 - Implementation areas: a) North Atlantic (WWIII) and b) A1 - Ireland's west coast (SWAN)

	Limits		
	Latitude	***Longitude***	***Resolution***
North Atlantic	(15ºN-72ºN)	(66ºW-7ºE)	1º x 1º
Ireland (A1)	(50ºN-57ºN)	(12ºW-6.5ºW)	3’ x 6’
Belmullet (A1.1)	(54ºN – 54.5ºN)	(10.5ºW – 10ºW)	0.5’ x 0.5’
Galway Bay (A1.2)	(52.4ºN - 53.6ºN)	(11ºW – 8.81ºW)	0.5’ x 0.5’
Galway Bay (A1.2.1)	(53ºN – 53.3ºN)	(9.7ºW – 8.89ºW)	0.1’ x 0.0612’

Table 1 - Computational grids for the wave hindcast system

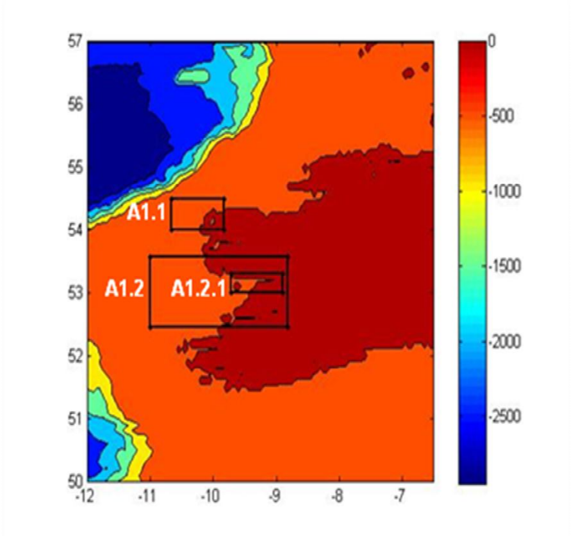

Figure 3 - Bathymetry of Ireland. Nesting areas in black: A1.1 – Belmullet (SWAN), A1.2 and A1.2.1 – Galway Bay (SWAN)

3 VALIDATION TESTS IN THE TIME DOMAIN

Measurements from four wave buoys owned by the Irish Department of Transport and maintained by the Marine Institute in cooperation with Met Eireann and the UK Met Office were used. Their location is shown in Figures 4 and 5 and specified in Table 2.

	Coordinates	*Depth*
Buoy 1	55º N,10º W	72 m
Buoy 2	51.217º N, 10.55º W	155 m
Buoy 3	54.231º N, 10.146º W	100 m
Buoy 4	53.227º N, 9.271º W	22 m

Table 2 - Coordinates and depth of the buoys considered

Figure 4 - Illustration of buoys 1 and 2 locations

a)

b)

Figure 5 - Illustration of the buoy locations: a) Buoy 3 (Belmullet) and b) Buoy 4 (Galway Bay)

Direct comparisons were made between the SWAN results and buoy data. For these validations, the time period considered was from 2010/05/23 at 00h to 2010/07/11 at 21h. The time resolution in question was of 3h for buoys 1 and 2 and 1h for buoys 3 and 4. Notice that some data from this time period may not be included due to buoy failure.

Figures 5 and 6 show the Significant Wave Height (Hs) and Figures 7 and 8 show the Mean Wave Period (Tm), each giving the comparisons between buoys 1 and 2 and the SWAN results for each point.

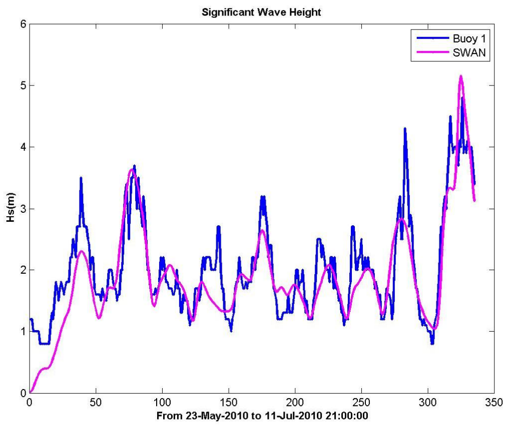

Figure 5 – Hs time series of Buoy 1 vs SWAN results.

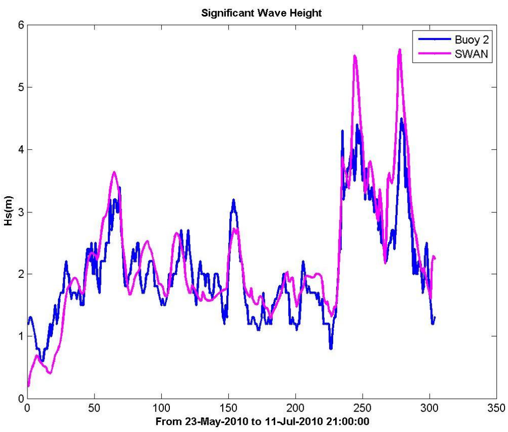

Figure 6 - Hs time series of Buoy 2 vs SWAN results

As can be seen in the time series presented for buoys 1 and 2, both Hs and Tm, SWAN's results have the same behavior as the buoys, keeping track of the various oscillations. For the two nesting areas, the Hs and Tm time series are showed in Figures 9 and 10, for Belmullet, and Figures 11 and 12 for Galway Bay.

In these cases, Hs is the parameter with better results, as in either location SWAN's results accompanied buoy's oscillations. For Tm, SWAN's outcome was not as good as desired, especially for Galway Bay's case.

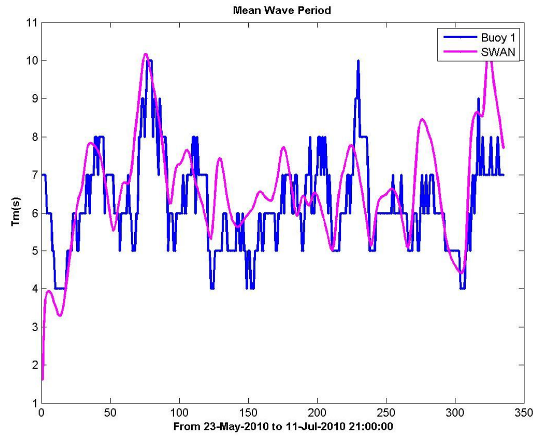

Figure 7 - Tm time series of Buoy 1 vs SWAN results

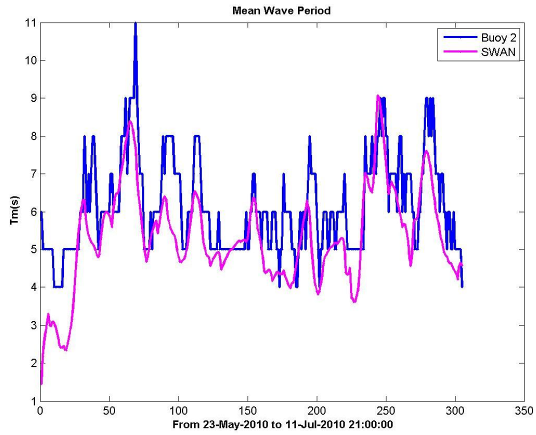

Figure 8 - Tm time series of Buoy 2 vs SWAN results

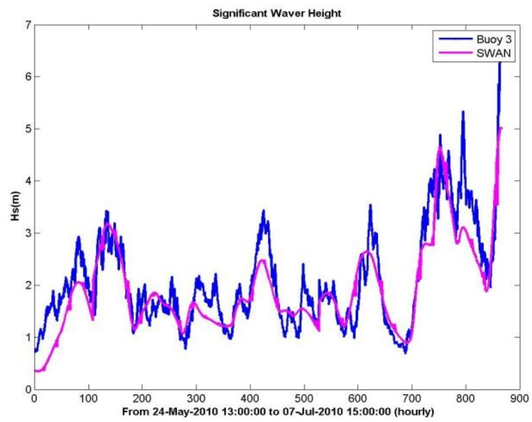

Figure 9 – Hs time series of Buoy 3 (Belmullet) vs SWAN results.

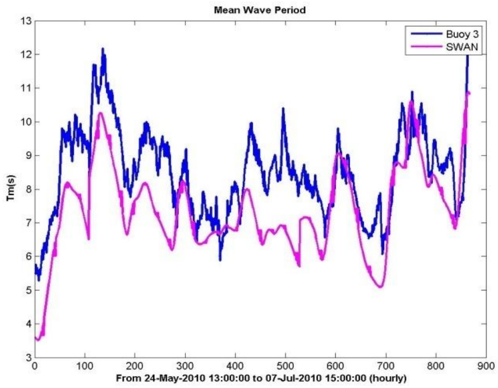

Figure 10 – Tm time series of Buoy 3 (Belmullet) vs SWAN results.

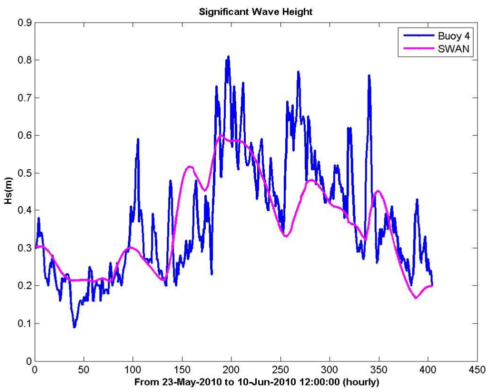

Figure 11 – Hs time series of Buoy 4 (Galway Bay) vs SWAN results.

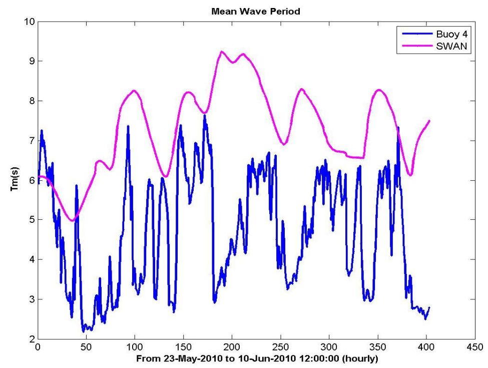

Figure 12 – Tm time series of Buoy 4 (Galway Bay) vs SWAN results.

To have a better understanding of the skill of the model, a statistical evaluation was made. The computed statistics were the average values of measurements (Bm) and simulations (Sm), the bias, root mean square error (RMSE), scatter index (SI) and Pearson's Correlation Coefficient (r) and can be expressed by the relationships:

$$Bm = \frac{\sum_{i=1}^{n} X_i}{n} \tag{7}$$

$$Sm = \frac{\sum_{i=1}^{n} Y_i}{n} \tag{8}$$

$$Bias = \frac{\sum_{i=1}^{n} (X_i - Y_i)}{n} \tag{9}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (X_i - Y_i)^2}{n}} \tag{10}$$

$$SI = \frac{RMSE}{\tilde{X}} \tag{11}$$

$$r = \frac{\sum_{i=1}^{n} (X_i - \tilde{X})(Y_i - \tilde{Y})}{\sqrt{\sum_{i=1}^{n} (X_i - \tilde{X})^2 \sum_{i=1}^{n} (Y_i - \tilde{Y})^2}} \tag{12}$$

Here X_i represent the measured values, Y_i the simulated values and n the number of observations. The results are shown in Table 3.

	Bm	Sm	Bias	RMSE	SI	r
Significant Wave Height						
Buoy 1 (n=335)	2.019	1.878	0.141	0.449	0.222	0.866
Buoy 2 (n=304)	2.060	2.204	-0.145	0.493	0.240	0.890
Buoy 3 (n=867)	2.083	1.909	0.174	0.479	0.230	0.886
Buoy 4 (n=404)	0.376	0.358	0.018	0.113	0.301	0.708
Mean Wave Period						
Buoy 1 (n=335)	6.221	6.641	-0.420	1.286	0.207	0.592
Buoy 2 (n=305)	6.118	5.296	0.822	1.238	0.202	0.735
Buoy 3 (n=867)	8.472	7.366	1.106	1.416	0.167	0.770
Buoy 4 (n=403)	4.641	7.274	-2.633	3.057	0.659	0.261

Table 3 - Statistical results for Hs and Tm, at each location

Some observations can be made at this point in relation to the statistical results. For Hs, in terms of RMSE, the model presents a discrepancy of less than 50 cm and the values are well correlated, this shows that the simulation results are close to the buoy measurements, being able to predict with minor error the wave conditions.

The SI is low and Bias shows that the model mostly underestimates buoy values. In terms of Tm, in the exception of Galway Bay, the RMSE and SI present good results and the correlation coefficients are over 0.5, which shows that the prediction system performs reasonably for this parameter, although with worst results, but however this is typical of period predictions. It can be noticed that the model gave worst results for buoy 2, concerning Hs, which is located where the waters are deeper. The outcome values for Galway Bay showed a different behavior in comparison with the other nested area. Having in mind that a two level grid was used for Galway Bay, comparing with Belmullet's nesting, Hs got better results but Tm got worst results.

For the analyses of the significant wave height, scatter plots are presented in the Figures 13 to 16, for the four buoy locations.

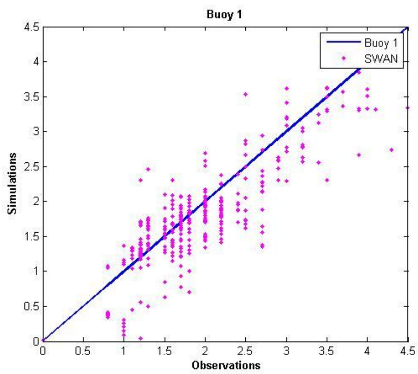

Figure 13 - Hs scatter plot for buoy 1

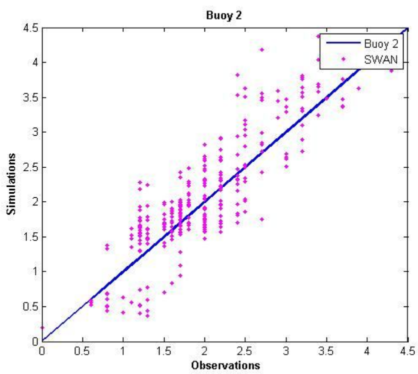

Figure 14 - Hs scatter plot for buoy 2

As seen in the scatter plots, most of SWAN results are below (Figure 13) or above (Figure 14) the observations line confirming the values obtained for Bias.

The same can be observed for the nesting areas, as the Figures 15 and 16 can illustrate.

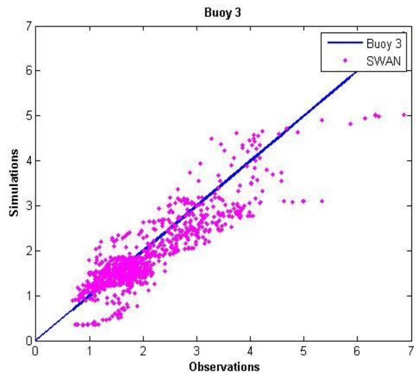

Figure 15 - Hs scatter plot for buoy 3 (Belmullet)

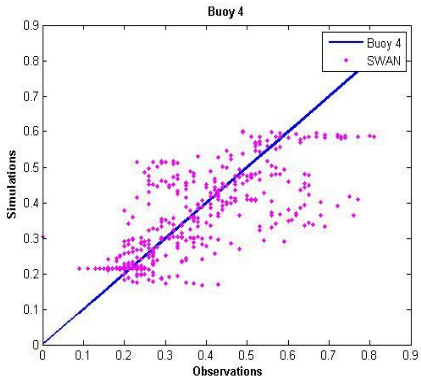

Figure 16 - Hs scatter plot for buoy 4 (Galway Bay)

It can be noticed that, for Belmullet's case, most SWAN results are below the observations line, while for Galway Bay they look almost evenly distributed.

4 WAVE ENERGY ASSESSMENT

In SWAN, the energy transport per unit of wave front (W/m), are calculated with the formula:

$$P_x = \rho g \int \int c_x E(\sigma,\theta) d\sigma \, d\theta \qquad (13)$$

$$P_y = \rho g \int \int c_y E(\sigma,\theta) d\sigma \, d\theta \qquad (14)$$

Here x,y are the problem coordinate system and c_x, c_y are the propagation velocities of wave energy in the geographical space defined as:

$$\frac{d\vec{x}}{dt} = (c_x, c_y) = \vec{c}_g + \vec{U} \tag{15}$$

Knowing that, wave power can be calculated by :

$$P = \sqrt{P_x^2 + P_y^2} \tag{16}$$

One case study was considered and analyzed. It corresponds to 2010/07/07, at 13h, where one of the highest values for Hs was encountered.

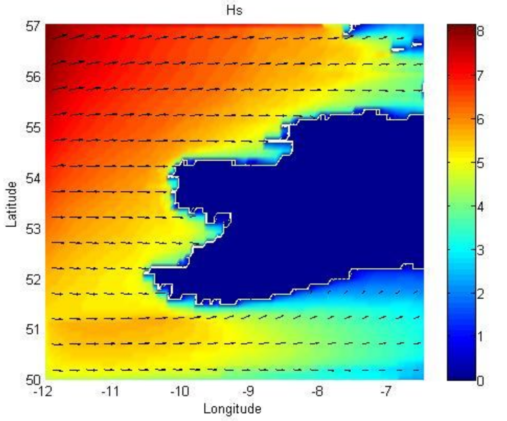

Figure 17 - Hs spatial distribution. In the background significant wave height scalar fields and in foreground wave vectors.

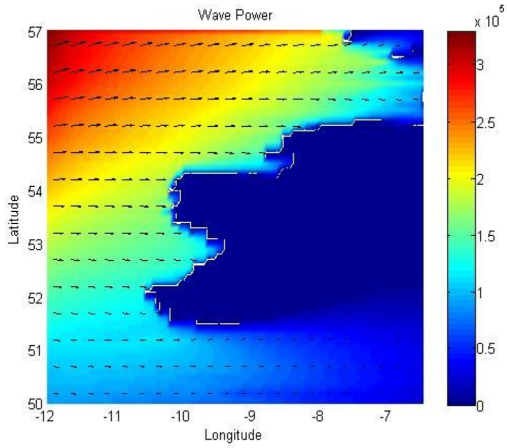

Figure 18 - Computed Wave power (W/m). In background wave power scalar fields and in foreground energy transport vectors.

Since higher wave energy values are observed in the north of Ireland, a spatial study for Belmullet was also done.

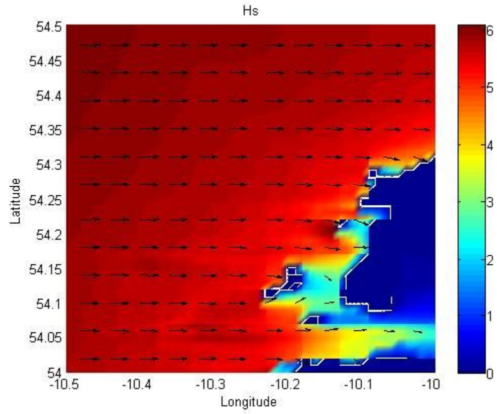

Figure 19 – Belmullet's Hs spatial distribution. In the background significant wave height scalar fields and in foreground wave vectors.

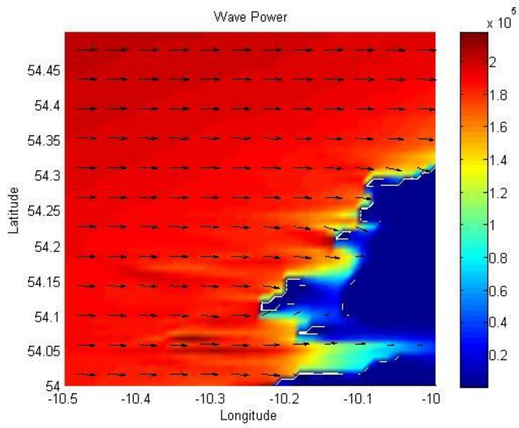

Figure 20 – Belmullet's computed Wave power (W/m). In background wave power scalar fields and in foreground energy transport vectors.

Clearly, the Irish west coast can register high wave energy values offshore and nearshore.

In this case study, wave direction is around 270º. When this happens, the incoming waves hit Ireland's west coast with high wave power, and while south Ireland has a shadow effect, north Ireland presents high energy values. Theoretical results demonstrate that with a significant wave height of around 5m, wave power can measure up to 160 kW/m, at Belmullet's buoy location.

5 CONCLUSIONS

A wave prediction system based on the two state-of-the-art spectral models, WWIII and SWAN, was used to evaluate wave conditions on Ireland's west coast, known as being highly energetic.

Since the wave power is proportional to the significant wave height and to the period of motion, by modeling the wave climate, theoretical values for the energy transport components can be assessed, which afterwards can give the absolute values of the energy transport, denoted also as wave power. A validation analysis of the computed results against buoy measurements gave a perspective on the accuracy of the numerical wave models close to the Irish coast.

Overall the wave prediction system gave good results when compared with the buoy data. For significant wave height the outcome was better than for the mean wave period, as was expected.

In terms of differences between the two offshore locations, the buoys are situated in different depths and that can influence the performance of the coastal model.

Analyzing the results from the two nested areas, it can be concluded that a better resolution in the geographical space, complemented with a higher quality of the bathymetry should lead to the improvement of the results for significant wave height.

Regarding energetic results, considering the case study and the quality of the performance of the wave prediction system, the results obtained for wave power can be accepted as being very near to the real potential of that area.

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